DESIGN OF EFFICIENT THERMOPHOTOVOLTAIC SYSTEM BASED ON META-MATERIAL NARROW-BAND EMITTER FOR SPACE POWER SUPPLY

by

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Photovoltaic technology has been widely used in spacecraft power supply, but its efficiency is difficult to be greatly improved by Shockley-Queisser limitation. The thermophotovoltaic technology can convert solar radiation energy or high temperature combustion energy into radiation energy with reshaped spectrum for direct photovoltaic power generation. In this study, a meta-material structure composed of metal tantalum, Ta, and dielectric SiO_2 is innovatively proposed for shaping narrowband radiation. The results show that the optimized spectral emittance peak of narrowband emitters reaches 0.9998. Narrowband emitter has advantages at high temperatures above 1000 K. The thermophotovoltaic efficiency of InGaAsSb cell and tandem Si/InGaAsSb cells can reach more than 41.67% and 46.26%, respectively. It is significantly higher than published thermophotovoltaic system with broadband emitter. This study demonstrates the notable advantages and potential of narrowband emitter for spectrum reshaping, which provides an important reference for future spacecraft power supply as well as space solar power generation.

Key words: *thermophotovoltaic, meta-material structure, spectrum reshaping, narrowband emitter, photovoltaic cell*

Introduction

With the rapid development of space technology, the exploration and utilization of space with the help of spacecraft has become an important issue for human beings to expand their living space and establish national defense systems. The power supply of spacecraft is the key for efficient and stable operation [1]. In energy conversion technology, compared with heat engines, PV technology has advantages of small, light, no rotating parts, and can directly output direct current. Thus, satellites and spacecraft mainly use solar PV panels as power source. However, only part of the solar spectral radiation can be utilized by PV cell, and it cannot effectively utilize radiation at lower frequencies. Thus, the efficiency of PV technology is limited. The experimental result of highest efficiency of Si PV cell is 27.6%. Therefore, a large area of PV panel is required to increase the obtained solar energy to meet the spacecraft power supply requirement. However, large area PV panel increases the spacecraft's own load and external volume, affecting the spacecraft performance. In addition, the temperature of PV cell will rise severely due to the radiation waveband that cannot be utilized. Thus, the performance decreases and a larger area cooling system is also required to cool the PV cell to overcome it [2]. There-

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fore, improving the energy conversion efficiency is the key to achieve efficient space power supply and promote the lightweight development of spacecraft [3].

In recent years, scholars have proposed thermophotovoltaic (TPV) technology, which can break through the traditional efficiency limit of PV system. The TPV using solar energy as heat source can absorb the entire solar spectrum radiation and then reshape the spectrum to effectively match the corresponding waveband of PV cell through selective emitter. It can effectively break the Shockley-Queisser limit [4, 5] and improve the system performance. In addition, TPV system for space power often use nuclear energy as a heat source [6], which can be used for deep space exploration. Thus, TPV has great potential to ensure the long-term operation of spacecraft, *etc*. Selective emitter with desirable emission properties is the key component in TPV system, which could reshape the emission spectrum and effectively enhance system efficiency. Due to the development of micro-nanotechnology, artificially designed meta-material structure has been introduced in TPV system to reshape the spectrum [7] for better match with the PV cell absorption spectrum. The efficiency of solar TPV based on micro/nanostructured selective absorber or emitter has been demonstrated to get the potential to breakthrough 50% [8]. It is generally accepted that the utilization of micro/nanostructured materials to achieve selective absorption and emission is the key to enhance the TPV efficiency [9]. There have been several studies on the design and comprehensive analysis of selective absorber and emitter for solar thermophotovoltaic (STPV) system. Chen and Shan [10] proposed micro/nanoselective absorber and emitter with cylindrical periodic structure for the space STPV system, which reveals great potential to realize the efficient utilization of AM0 solar radiation for space power supply. Rana *et al*. [11] designed selective absorber and emitter based on Cr metasurface for high STPV efficiency, and the simulated and measured results of absorptance/emittance characteristics are basically consistent. For selective emitter for spectral reshaping, Maremi *et al*. [12] designed a selective emitter with a multilayer ring meta-material structure to match InGaAs PV cell, which could achieve a spectral efficiency of 79.6% at 1400 K. Rinnerbauer *et al*. [13] designed and fabricated a photonic crystal emitter based on Ta cylindrical hole array, which was experimentally determined to have nearly 100% emissivity below 1.9 μm. Gu *et al*. [14] proposed a 2-D pyramidal meta-material nanostructured emitter with attractive selective emission properties based on Ta and SiO_2 materials, whose normal emittance is close to 1.0 in the wavelength range of 0.3-2.0 μm and dramatically decreases at wavelengths beyond 2.0 μm. In order to improve the TPV efficiency, Lou *et al*. [15] proposed a technical solution using multiple cells, which can achieve the TPV efficiency of more than 25% for blackbody radiation. Recently, Chen *et al*. [16] proposed a TPV system with energy storage and designed a meta-material emitter for medium-low temperature, which achieved a system efficiency of 24.24% at 1000 K, providing a possibility for medium low temperature TPV conversion. Liu *et al*. [17] proposed a design strategy of selective emitter whose meta-surface is designed with periodically W nanodisks patterned with circles and squares. The emittance spectrum can match to various TPV cells by simply changing the size and period of the meta-atoms in meta-surface of emitter. Chen *et al*. [18] designed and fabricated emitters with two geometric types (hexagon and square) of the array patterns based on the refractory material W. The emitter is fabricated by photolithography followed by metal deposition, which provides guidance for fabrication of emitter in the future study. The various types of meta-material selective emitters that have been studied are mostly broadband emitters, whose core consideration is to cover the entire responsive waveband of PV cell (all waveband above the cut-off frequency of cell). Therefore, the selective emitter is significant for a high TPV system efficiency. However, when the photon energy is greater than the band-gap energy, the high frequency photon with has a lower PV conversion efficiency than low frequency photon since the inherent irreversibility. Therefore, narrow-band emitter, which highly matching TPV cell, reduces the excitation of electrons using high energy photons. Thus, the TPV system efficiency with narrowband emitter should be higher than that with broadband emitter theoretically, which has not been addressed in previous studies.

According to the aforementioned background, the innovative work of this study is summarized:

– A meta-material narrowband emitter with cross patch as the main regulator is designed especially based on Ta and SiO_2 to match InGaAsSb cell for TPV device in space engineering.
– Through optimizing the parameters of each layer thickness, cross length and width, a suitable geometrical structure size is obtained and its physical regulation mechanism is analyzed via electromagnetic theory.
– An effective scheme, which matching Si/InGaAsSb tandem PV cells with the narrowband emitter, is proposed to futher improve the system efficiency at high temperature. It is found that the solution can achieve a power generation efficiency of over 40%, which is much higher than that of solar PV and comparable to the highest efficiency of available thermal power cycle. Its performance is better than many published broadband meta-material emitters, fully demonstrating the potential of current design and providing theoretical support for its practical application in space power supply.

Materials and methods

Space TPV model

Considering the demand for miniaturized power source in space, this study proposes a TPV system with meta-material-based emission spectrum reshaping, where the meta-material selective emitter is the main component of TPV system. The system energy conversion process is shown in fig.1, where both single InGaAsSb cell and Si/InGaAsSb tandem TPV cells can be used. Nuclear reaction energy, solar radiation energy, and combustion energy can be utilized as heat source in the spacecraft to heat the emitter to a high temperature. Selective emitter converts thermal energy into radiation energy with reshaped narrowband spectrum, which can achieve efficient matching with absorption spectrum of PV cell. Thus, the spectral efficiency is improved, and high TPV efficiency is achieved.

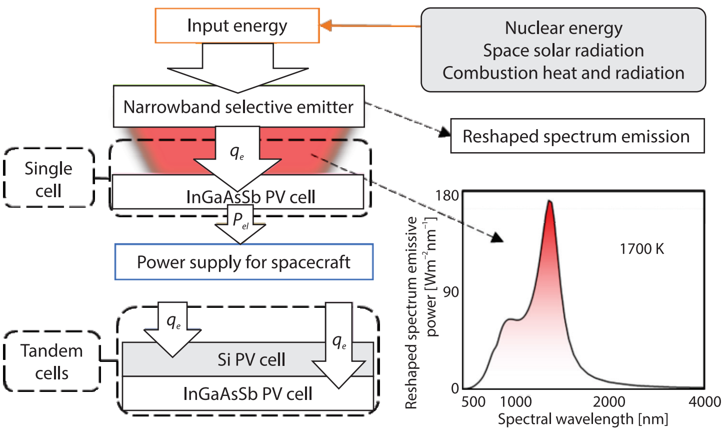

Figure 1. Schematic for system energy conversion process

The total incident solar radiation power of system is q_{solar}:

$$q_{\text{solar}} = \int_0^\infty G_{\text{solar}}(\lambda)\,\text{d}\lambda \tag{1}$$

where λ is the solar radiation wavelength and $G_{solar}(\lambda)$ – the solar spectral radiation intensity based on AM0 solar spectrum at λ. Generally, the solar spectral radiation intensity is calculated using standard spectra. The AM0 or AM1.5 spectra are used for space and ground conditions, respectively [10].

In the TPV system, radiation energy produced by selective emitter q_e can be calculated:

$$q_{\text{e}} = \int_0^\infty E_{\text{b}}(\lambda, T_{\text{e}})\,\varepsilon_{\text{e}}(\lambda)\,\text{d}\lambda \tag{2}$$

where λ is the wave length, $E_b(\lambda,T_e)$ – the blackbody radiation intensity and $\varepsilon_e(\lambda)$ – the emittance of emitter at the wavelength of λ. The reshaped emission spectrum is absorbed by tandem cells, converting radiation energy into electric energy.

For the calculation of TPV cell model, the TPV cell power can be written as [19]:

$$P_{\text{el}} = \int_0^\infty V_{\text{oc}} FF \frac{q_0 \lambda}{\text{hc}} EQE(\lambda)\,\varepsilon_{\text{e}}(\lambda)\,E_{\text{b}}(\lambda, T_{\text{e}})\,\text{d}\lambda \tag{3}$$

where V_{oc} is the open circuit voltage, FF – the fill factor, q_0 – the elementary charge, (= $1.60 \cdot 10^{-19}$ C), h – the Planck constant, (= $6.626 \cdot 10^{-34}$ Js), c – the speed of light, (= $3.0 \cdot 10^8$ m/s), and $EQE(\lambda)$ – the external quantum efficiency of InGaAsSb [20] cell and Si [21] cell.

After that, the open circuit voltage V_{oc} can be calculated [22, 23]:

$$V_{\text{oc}} = \frac{\Gamma k T_{\text{c}}}{q_0} \ln\left(\frac{J_{\text{SC}}}{J_0} + 1\right) \tag{4}$$

where Γ is the diode ideality factor (taken as 1), k – the Boltzmann constant, and T_c is the temperature of cell. Furthermore, J_0 is shown [22, 23]:

$$J_0 = 1.5 \cdot 10^5 \exp\left(\frac{-E_{\text{g}}}{k T_{\text{c}}}\right) \tag{5}$$

where E_g is the bandgap of PV cell.

Finally, the fill factor FF is calculated [22, 23]:

$$FF = \beta \frac{v - \ln(v + 0.72)}{v + 1} \tag{6}$$

$$v = \frac{q_0 V_{\text{oc}}}{k T_{\text{c}}} \tag{7}$$

where β is the correction factor, which is 0.96 [22, 23].

Finally, the TPV conversion efficiency η_{TPV} can be calculated:

$$\eta_{\text{TPV}} = \frac{P_{\text{el}}}{q_{\text{e}}} \tag{8}$$

For the calculation of tandem cells, according to [24], the TPV efficiency of the top cell that has higher bandgap is calculated firstly, and the bottom cell only has access to the photons with lower energies which have are not absorbed by the top cell. Thus, the Si cell with a relatively higher bandgap is placed at the top, and the InGaAsSb cell with a lower bandgap is placed at the bottom. This design can reduce the heat loss caused by the photon radiation with a frequency lower than the bandgap. Under reasonable assumptions, the two sub-cells can be modeled separately. Tunnel junctions are modeled in the form of a cap layer and there is assumed to be no voltage loss in the junction. The modelling of the second sub-cell has no effect on the first sub-cell, the second sub-cell could use available photon flux not absorbed by the fist sub-cell [25]. As a result, the utilization of tandem cells can theoretically improve the efficiency of system. According to the spectral *EQE* of PV cell, the selective emitter is optimized to obtain selective narrowband emission spectrum with a high match to the absorption spectrum, so as to obtain a high TPV conversion efficiency and ensure that the absorbed energy can be efficiently utilized by the PV cell.

Structure and performance analysis of selective emitter

The geometry of the meta-material selective emitter and the structural parameters are shown in fig. 2. The emitter is a micro/nanostructure based on a metal Ta, substrate with periodic structure length p in x- and y-directions, and the second layer is a SiO_2 dielectric with the same periodic structure length as the Ta substrate. The thicknesses of the rectangular Ta substrate and SiO_2 are t_0, t_1, respectively. The material of two-layer cross patch from bottom to top is Ta and SiO_2, respectively, both with the same thickness t_2. The length and width of the cross are b and c. In this study, the periodicity length for selective emitter is taken as p = 640 nm. The thickness of bottom Ta substrate is t_0 = 100 nm, thicker metal substrate can effectively reduce the transmission of spectrum. Higher TPV efficiency can be obtained by optimizing selective emitter and matching it with InGaAsSb PV cell, and the final values of structural geometric parameters of the selective emitter are, t_1 = 130 nm, t_2 = 18 nm, b = 300 nm, and c = 100 nm, respectively.

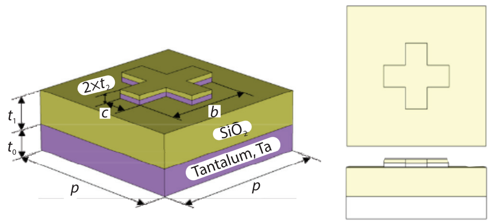

Figure 2. The geometry and structural parameters of selective emitter

The Maxwell's system of equations is solved through finite difference in time domain (FDTD) method [26] to simulate the emission properties of micro/nanostructured emitter. In this study, the emission properties of emitter are calculated in the wavelength range of 300-4000 nm. The optical parameters of the Ta metal and the SiO_2 dielectric materials for emitter are obtained from the Palik [27] optical handbook. The metal Ta, utilized as the substrate material of selective emitter, has good narrowband radiation characteristics with a peak emissivity greater than 0.6 in the wavelength range less than 800 nm. Thus, narrowband emission can be achieved by designing micro/nanostructured patches, which is conducive to improving the efficiency of PV cell. The cross patches proposed in this study play the key role to shape an efficient narrowband emission spectrum.

According to Kirchhoff's law [28], the emissivity of an object is equal to its absorptivity under thermodynamic equilibrium condition. During the process of simulation, the Scattering parameters (S-parameters) are obtained by incident planar electromagnetic waves vertically from above the emitter along the z-axis under thermodynamic equilibrium condition. The emittance of selective emitter is calculated:

$$\varepsilon(\lambda) = 1 - |S_{11}|^2 - |S_{21}|^2 \tag{8}$$

where $\varepsilon(\lambda)$ is the emittance of emitter at wavelength λ and S_{11} and S_{21} are the reflection and transmission coefficient, respectively. Due to the relatively large thickness of the underlying Ta substrate, it is difficult for electromagnetic waves to transmit, the value of S_{21} is close to 0. The formula for the emittance can be further simplified [26]:

$$\varepsilon(\lambda) = 1 - |S_{11}|^2 \tag{9}$$

The effective impedance z of micro-nanostructure is obtained from the S-parameters. The real part Re(z) and the imaginary part Im(z) of effective impedance can reflect the impedance matching degree between micro/nanostructure and free space, thus providing a micro/nanomechanical explanation for the emission properties of the micro/nanostructure [29]:

$$Z = \sqrt{\frac{(1+S_{11})^2 - S_{21}{}^2}{(1-S_{11})^2 - S_{21}{}^2}} \tag{10}$$

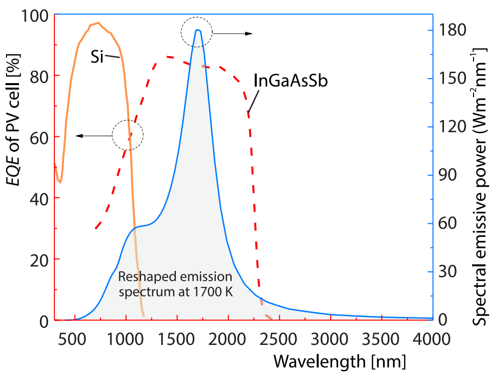

Figure 3. The *EQE* curve of Si and InGaAsSb PV cells and reshaped emission spectrum by selective narrowband emitter

Results and discussion

A meta-material selective emitter for narrowband spectrum is designed to match InGaAsSb PV cell, and Si/InGaAsSb tandem PV cells can also be matched by narrowband emitter for a higher TPV efficiency. The *EQE* curve of cells and the emission spectrum reshaped by the selective emitter are shown in fig. 3. It obviously shows that narrowband emission spectrum is almost covered by *EQE* curve of InGaAsSb PV cell [20], indicating the significance of selective emitter. Thus, a high spectral efficiency and a high TPV efficiency are achieved.

Theoretically, the energy of emission spectrum must be higher than the bandgap of cell to excite electrons. A photon can excite an electron. It should be noted that the short wavelength photons have a high frequency and high energy, but still only excite one electron, thus, the energy conversion efficiency will decrease. The closer the emission spectrum to the cut-off band of PV cell, the higher the TPV efficiency will be achieved. In view of this, the narrowband emitter designed makes emission spectrum close to the cut-off wavelength of cell, and inhibits the short-waveband emission with high energy, so as to effectively reduce the waste in the process of high frequency energy conversion. Its performance is better than the broadband emitter that can fully cover *EQE*. Therefore, narrowband emitter increases the energy utilization efficiency and thus the TPV efficiency.

Geometrical structure parameters analysis of meta-material emitter

In order to obtain a perfect narrowband emission spectrum, the geometrical structure parameters of micro/nanostructured emitter are optimized for a more desirable emission performance. Therefore, the influence of the geometrical parameters on emitter's performance is investigated.

To clarify the specific effect of the cross structure on the emitter emittance, a parametric scan of the cross structure is performed in this study. Figure 4 shows how the thickness of

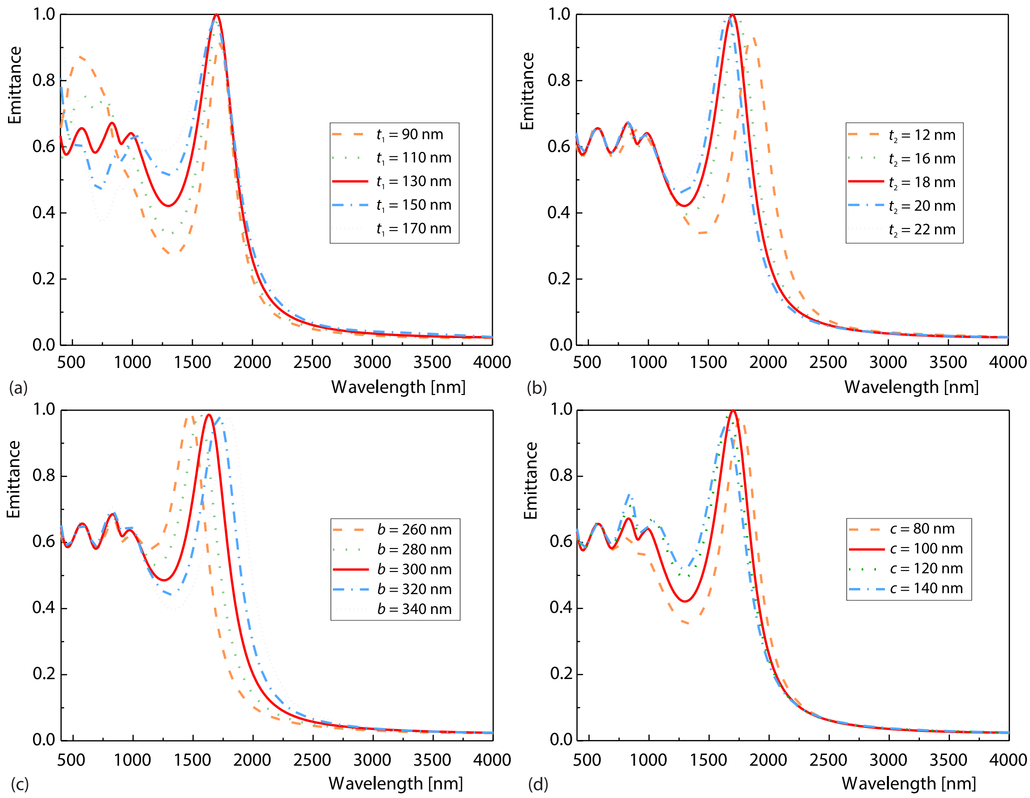

Figure 4. Variation of selective emitter emittance with; (a) thickness t_1 of the second dielectric SiO_2 layer, (b) thickness t_2 of the third and the fourth cross patch layers, (c) length b of cross patch, and (d) width c of cross patch

SiO_2 dielectric layer as well as the length, width, and single layer thickness of cross patch affect the emitter emission characteristics. The underlying metal Ta substrate is effective in blocking radiation transmission at a thickness t_0 = 100 nm, and the periodic length p of structure varies with almost no effect on the emittance. Figure 4(a) shows the variation of the emitter emission spectrum with the thickness t_1 of second SiO_2 dielectric layer, five equally spaced emittance values are calculated as t_1 changing from 90-130 nm (Δh_1= 20 nm). With the increase of t_1, there is higher emittance at the spectrum peak, which has the similar wavelength. However, it can be seen that the emittance closest to 1 and curve fluctuation tends to be smooth when t_1 = 130 nm. The emittance gradually increases with t_1 in the wavelength range of 1000-1500 nm. when t_1 is greater than 130 nm, the curve fluctuation enhanced again and it is in the opposite direction compared to the lower t_1 condition. Thus, the thickness of SiO_2 t_1 = 130 nm is selected.

Figure 4(b) shows the variation of the selective emission spectrum with the thickness t_2 of the third and fourth cross patch layers. It can be seen that the thickness of cross patch has a certain influence on location and intensity of the emission peak. The peak emittance increases with t_2, and it is closest to 1 when t_2 = 18 nm, then decreases with t_2. That is, t_2 = 18 nm is also a critical value affecting peak emittance variation. Furthermore, the wavelength corresponding to the peak moves slightly to the short-wavelength direction with t_2 increases, and the emittance between 1000-1500 nm increases, but the overall fluctuation is not great. Since this study is to investigate the performance of narrowband emitter, a rational t_2 of 18 nm is selected, which provides the highest spectral emittance peak but not a great total emittance.

Figure 4(c) shows the effect of cross patch length *b* on the emission spectrum, the length *b* has almost no effect on the intensity of peak emittance. However, the wavelength corresponding to the emittance peak moves to the long-wavelength direction with *b* increases. Thus, the narrowband emitter can be designed to match TPV cells with different cut-off bands by changing the length of cross patch. In addition, for blackbody radiation, the spectral radiation peak moves to the short-wavelength direction with the temperature. Therefore, changing the length of cross patch to adapt different temperature conditions could achieve optimal TPV efficiency. Figure 4(d) shows the effect of cross patch width *c* on emission spectrum. With the increase of *c*, the variation of emission intensity peak first increases and then decreases although the variation is not very obvious. The spectral emittance peak slightly shifts to the short-wavelength direction. The peak emittance is closest to 1 when c = 100 nm. Moreover, the spectrum emittance in the waveband of 1000-1500 nm increases with *c*. Thus, this study selects *c* as 100 nm considering the requirement of narrowband emission,

Therefore, the geometric structure parameters of the narrowband selective emitter are t_1 = 130 nm, t_2 = 18 nm, b = 300 nm, and c = 100 nm, and the wavelength corresponding to the peak emittance of emitter is around 1700 nm.

Angle sensitivity and polarization dependence of meta-material emitter

In practical applications, the emitter has different emission characteristics at different space angles. For the designed narrowband spectrum emitter, its emission characteristics at different polarities and polarizations need to be explored and its sensitivity to polarity and light incidence angle should be verified.

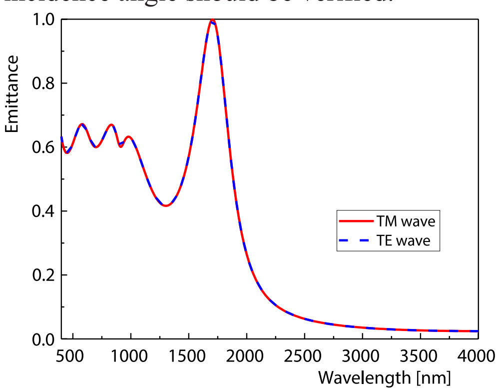

Figure 5. Emittance spectrum in TM and TE polarization modes

The ideal TPV emission should be not only wavelength selective but also polarization insensitive so that high emissivity of transverse electric (TE wave or s-polarization) and transverse magnetic (TM wave or p-polarization) waves can be achieved [30]. The emittance distribution of emitter under the action of two polarization modes, TE wave (φ = 0°, electric field along *x*-direction) and TM wave (φ = 90°, electric field along *y*-direction), is discussed. The result can be seen from fig. 5 that there is no significant difference in the spectral emittance under the two polarization modes. Thus, the emitter is polarization insensitivity, and the emission spectrum is independent of the plane wave polarization. Therefore, the subsequent discussion is only for the emission spectrum under the effect of TM wave.

Furthermore, fig. 6 shows the variation of emission spectrum when the spectral incidence angle θ varied from 0-60° at equal intervals (15°). There is almost no shift in the emittance peak as the incidence angle θ increases from 0-45°, and there is no strong fluctuation in the main waveband, all of which has perfect emission characteristics and can match well with the InGaAsSb PV cell. When θ increases to 60°, the fluctuation becomes greater in the short waveband, but it still has the narrowband emission characteristic. The emitter has less effect on spectrum reshaping in short waveband since the spectral radiation intensity in short waveband is inherently low under the general engineering application temperature. Therefore, the selective emitter can still achieve a good spectrum reshaping for blackbody radiation. Furthermore, it indicates that the emitter is not sensitive to the polarization angle and has good working stability within a certain polarization angle range. For the emission of solid materials in real space, the engineering is generally concerned about the normal emittance ($\theta = 0$ °) [31], so the designed selective emitter can achieve higher TPV efficiency.

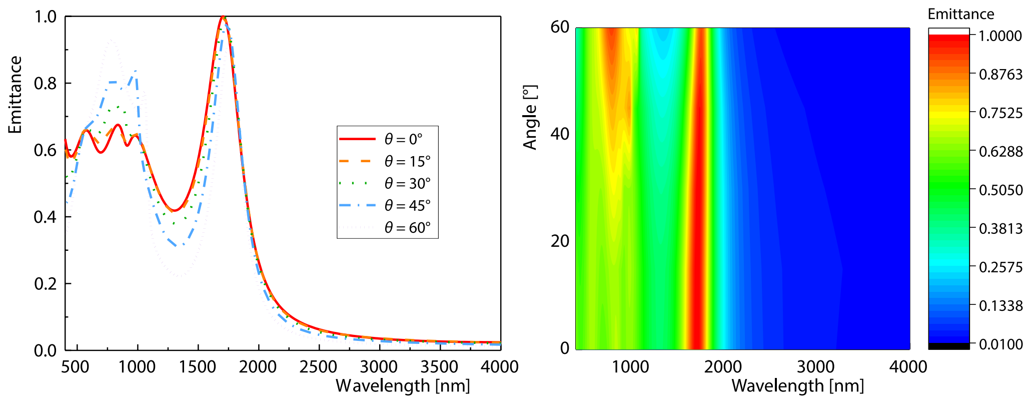

Figure 6. Emission spectrum and 3-D distribution of emitter under different incidence angles

Spectral modulation mechanism of meta-material selective emitter

To explore the radiation modulation mechanism of the selective emitter, the electric field, |***E***|, and magnetic field, |***H***|, distribution within the emitter at the wavelength (1700 nm) that corresponding to the emittance peak is analyzed, and the results are shown in fig. 7. It can be seen that the |***E***| and |***H***| distributions of the emitter are centrosymmetric. The |***E***| and |***H***| in the *xoy* plane mainly distribute at the interface of the second dielectric SiO_2 layer and the third metal Ta cross patch layer. The structure bottom is the starting point (0 point) of the *z*-axis, so the interface is at $z = t_0 + t_1$=230 nm. In the *yoz* plane, the center point of the micro/nanostructure is the starting point (0 point) of the *x*-axis. Figure 7 shows the distribution of |***E***| and |***H***| is at the cross-section of $x = b/2 = 50$ nm. From the *xoy* plane, the interface of SiO_2 rectangle and Ta cross patch exhibits stronger electric and magnetic fields, and |***E***| and |***H***| are centrosymmetrically distributed in the structure, indicating that the designed structure has a strong symmetry. From the *yoz* plane, the electric and magnetic fields are also stronger at the cross patch laminated structure along *z*-axis direction. It indicates that the higher emittance of selective emitter at wavelength of 1700 nm is mainly modulated by the cross patch. That is, the cross patch plays a major role in creating narrowband selective emission.

Surface plasmon polaritons (SPP) refer to plasma oscillations of free electrons resonantly ex-cited by incident light at a metal-dielectric interface. Local surface plasmon resonance (LSPR) refers to the collective oscillation of conduction band electrons at the interface of metallic structure [29]. The high emittance of emitter is exhibited through the excitation of plasma excitations within the structure. Accordingly, it can be found that there is a strong magnetic field in the dielectric-metal-dielectric laminated structure and also a strong electric field is generated at edge of laminated structure, which indicates that SPP are ex-cited at the metal-dielectric interface. At the same time, Ta cross patch appears strong magnetic field, and its surrounding exhibits strong electric field, which is the result of LSPR. The narrowband emittance is achieved under the combining effect of SPP and LSPR in the selective emitter. The narrowband selective emitter can effectively reduce the excitation and utilization of too high frequency photons as well as low frequency photons, which has a positive effect on achieving a high TPV efficiency.

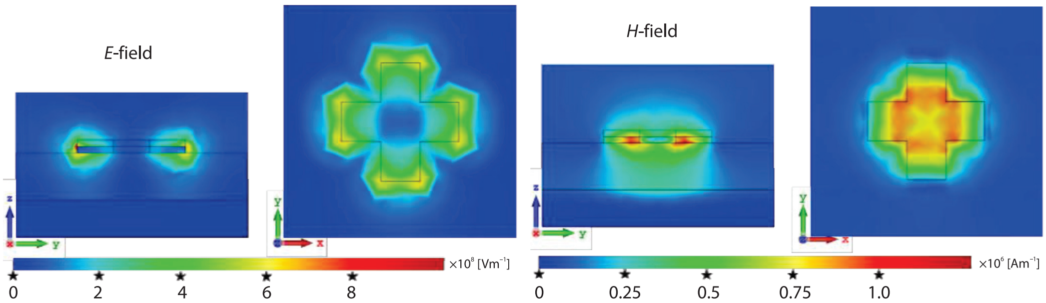

Figure 7. Electric field, |*E*|, and magnetic field, |*H*|, distribution of selective emitter at wavelength of 1700 nm

Effect of meta-material selective emitter on system performance

The intensity of blackbody radiation increases with temperature, and the spectrum peak moves to the short-wavelength direction. The loss of photon energy is minimized and the theoretical electrical conversion efficiency is highest when the photon energy is slightly higher than cell band-gap energy. The selective emitter designed in this study is a narrowband emitter with a peak at wavelength of 1700 nm. When the wavelength peak of blackbody radiation is like that of the narrowband selective emitter, the selective emission spectrum with high energy intensity can be obtained through spectrum reshaping effect of selective emitter. The waveband corresponding to the absorption spectrum of InGaAsSb PV cell and Si/InGaAsSb tandem PV cells used in this study is 500-2400 nm and 380-2400 nm, respectively.

When the temperature of blackbody is lower than 1000 K, the spectrum peak is at the wavelengths greater than 3000 nm, and the available energy distribution ratio is low in the short waveband. The respond spectrum of Si cell is in the short waveband. Thus, there is little difference in TPV efficiency between single InGaAsSb cell and tandem Si/InGaAsSb cells when the temperature is lower than 1000 K as shown in fig. 8 (selective emitter and blackbody emitter is represented as SE and BE in fig. 8, respectively. However, as the temperature increases, the energy density of the radiation spectrum increases, and the spectrum shifts toward the short-wave direction. Thus, the utilization of Si cell becomes progressively more effective in improving TPV efficiency. It can be seen that the TPV efficiency increases significantly with the temperature, which is because the emission intensity in effective waveband increases with temperature. When the temperature is about 1700 K, the system efficiency with narrowband emitter combined with single PV cell can reach 41.68% due to the radiation spectrum peak at temperature of 1700 K is closer to the emittance peak of selective emitter (1700 nm). Furthermore, the efficiency of system based on Si/InGaAsSb tandem cells can reach 46.26%, that is the utilization of Si PV cell increases TPV efficiency by 4.58 %. Thus, the spectrum is better reshaped.

The selective emitters that with broadband emission properties experimented by Jeon *et al.* [32] and that with high temperature thermally stable based on natural materials for TPV measured by Tobler and Durisch [33] are matched with tandem cells proposed in this study, the

TPV efficiency is shown in fig. 8. The maximum TPV efficiency is only about 38% at 1700 K, which is lower than the proposed narrowband emitter by 8 percent point. Considering the actual solar radiation intensity, the absorption efficiency of selective absorber can reach over 90% in a typical STPV system [10], so it is estimated that the efficiency of the STPV system based on current narrowband emitter is 7% points higher than that based on previous emitter. This fully illustrates the advantages of the narrowband emitter of this paper. Figure 8 also presents the TPV efficiency of blackbody emitter match the GaSb/InGaAsSb tandem cells proposed by Lou *et al.* [15]. This indicates the superiority of narrowband emitter, which is more suitable for space power supply.

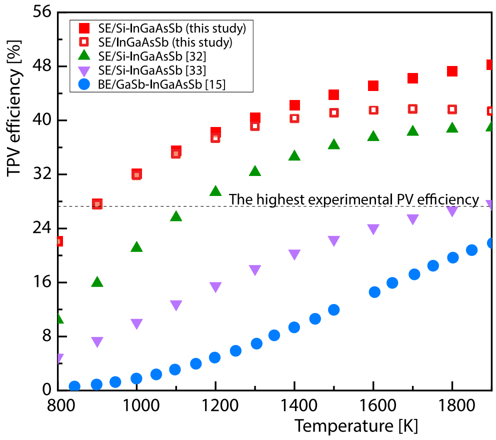

Figure 8. Comparison of the different TPV systems efficiency with temperature

Conclusions

This study proposed a meta-material narrowband emitter composed of Ta and SiO_2 for InGaAsSb PV cell, constructing a high efficiency TPV system for space power supply. The designed selective emitter could reshape the high temperature blackbody radiation spectrum so that it can match well with the PV cell. After optimizing its geometrical structure parameters, better emission properties and higher TPV performance are obtained. The emission mechanism of the meta-material structure is also analyzed. The main conclusions are as follows.

- A narrowband meta-material selective emitter based on Ta and SiO_2 is constructed to match InGaAsSb TPV cell, and the geometrical structure parameters of emitter are optimized as $t_1 = 130$ nm, $t_2 = 18$ nm, $b = 300$ nm, $c = 100$ nm, and $p = 640$ nm to obtain good spectrum characteristics. The peak emittance (at wavelength of 1700 nm) of emitter can reach about 0.9998.
- For the meta-material composed of Ta and SiO_2 laminated structure, the cross patch plays a major role in spectral modulation than the underlying layers. The narrowband emittance is achieved mainly by the combining effect of SPP and LSPR ex-cited in the selective emitter. In the waveband of selective emission, SPP are ex-cited at the metal-dielectric interface of the cross patch. The LSPR excites the strong magnetic field and electric field in and around the Ta cross patch. The excitation of LSPR causes a strong magnetic and electric field in and around the Ta cross patch.
- High TPV efficiency can be achieved by using narrowband selective emitter. Narrowband emitter has significant advantages at high temperatures above 1000 K. The TPV efficiency of InGaAsSb PV cell and tandem Si/InGaAsSb PV cells increases with temperature and reaches 41.68% and 46.26% at the temperature of 1700 K, respectively, which is higher than the previous published emitter by 8% point. The simple technical route of narrowband emitter matched single-stage PV cell achieves high efficiency and provides theoretical and technical guidance for TPV system in future space power supply.

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Contribution

Authors Heng Li and Jialu Tian equally contributed to this work.

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